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Spectroscopic and photometric analysis of three detached binary systems: AP And, VZ Cep and V881 Per

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ABSTRACT

We present results from analysis of combined spectroscopic and photometric data for three eclipsing binary systems: AP And, VZ Cep and V881 Per. Based on new, multicolour photometric light curves and spectroscopically determined mass ratio values, we derived accurate physical parameters of the components. Two of the systems, namely VZ Cep and V881 Per, were found to be magnetically active. The variability of V881 Per was studied in several sets of data [Northern Sky Variability Survey (NSVS), Wide Angle Search for Planets (WASP) and newly derived] gathered at different epochs. We show that the huge differences in the shape of its light curve can be explained by just a single model differing only in number of spots and their location on the surface of the primary component.

Key words: binaries: eclipsing – stars: evolution – stars: fundamental parameters – stars: individual: AP And – stars: individual: V881 Per – stars: individual: VZ Cep.

1 INTRODUCTION

Eclipsing binary systems provide the means to measure empirically fundamental parameters of stars, such as stellar masses, radii and luminosities, which are of great importance in studies of stellar structure and evolution. Especially, well-detached binaries, components of which essentially evolve as single stars, may provide precise and accurate fundamental parameters which, in turn, will provide important constraints on not so well-known aspects of stellar evolution and structure (e.g. influence of rotation or strong magnetic fields on inner stellar structure, investigate the role of different physical processes, or test the General Relativity theory). A recent, most numerous compilation consisting of most accurate and uniformly determined parameters of 95 detached binaries was published by Torres, Andersen & Gimenez (2010).

Eclipsing binaries with a pulsating component are of special interest. Several such systems containing a classical Cepheid-type variable component have been recently found (Pietrzynski et al. 2010). These authors, after disentangling the light curves of a pulsating component and that originating due to eclipses, were able to determine the dynamic mass of the Cepheid star and resolved the long-standing disagreement, indicating that pulsational masses agree well with their independent determination.

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The main goals of this work are (a) derivation of the fundamental parameters of components of three eclipsing binary systems: AP And, VZ Cep and V881 Per, through their light and radial velocity curve analysis, (b) description of their evolutionary status and (c) explanation of the light curve changes of the most active system V881 Per out of the three studied here. The paper is organized in the following way: description of former results on the chosen systems follows in this section, Section 2 and 3 present new spectroscopic and photometric observations, details of the light-curve modelling are described in Section 4 and discussion of obtained results concludes the paper.

AP And

The light variability of AP And (GSC 3639-00915) was first discovered by Lassovszky (1931), who later determined its period as 0.793 65 d and published the first light curve from photographic data (Lassovszky 1932). Since for this period estimation the secondary minimum was absent, he also suggested the period to be twice longer. Based on Lassovszky's data, Kopal (1932) estimated the orbital parameters of the system. The first period study of AP And was performed by Whitney (1957), who determined the period to be 1.587 2920 d and mentioned that the orbital period of the system was constant. The first photographic light curve of the system with two minima times were obtained by Daube (1969). The physical parameters of the system were determined by a statistical method by Brancewicz & Dworak (1980). They also estimated the spectral type of the more luminous component as F5, while Wood, Parker & Koch (1980) assigned the spectral type of the hotter component as F6. Giuricin, Mardirossian & Mezzetti (1984) in their study of

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unevolved close binary systems assumed the same spectral type for the hotter component and F8 for the cooler one.

The first photoelectric *BV* band light curves of the system were obtained by Vandenbroere (1993). She found the $B - V$ index as 0.55 and mentioned that the system is an eclipsing binary whose primary and the secondary minima cannot be discriminated.

Before that, and in subsequent years, only observations of the times of mid-eclipse were performed (Romano & Perissinotto 1969; Agerer & Hübscher 2003; Lacy 2003, 2004, 2006, 2007; Dvorak 2005; Hübscher, Paschke & Walter 2005, 2006; Nelson 2006; Hübscher & Walter 2007; Hübscher 2011; Liakos & Niarchos 2011).

VZ Cep

VZ Cephei (GSC 04470-01334) was discovered as a variable star by Gengler, Blazhko & Schneller (1928) who gave a variability range between 9.4 and 9.8 mag but could not classify the light curve type. The first spectral type determination of the system was performed by Cannon (1934), as G0. Further observations were done by Romano (1962) that showed irregular light variability in the range 9.3–10.0 mag. The first photometric measurements of VZ Cep were carried out by Rössiger (1978) leading to a conclusion that it is an eclipsing binary system with a period of 1.18336 d.

The system was investigated by Lacy (1992) and Lacy (2002) under the photometric surveys of eclipsing binary stars in which the Johnson wide band and Strömgren colours of the system were obtained.

Because of its relatively late spectral type, Popper (1996) included it as a target in his programme to search for late-type (F–K) eclipsing binary stars. On the basis of four spectra, he concluded that both components were likely hotter than G0, and he estimated the mean system spectral type to be middle F (F2–F5). He also derived the lower total mass limit to be 2.4 $M_{\odot}$.

The first detailed photometric and spectroscopic investigation of the system was performed by Hicks (2007). Using a 25 cm telescope at the University of Arkansas, he obtained its light curve in the Bessell *V* filter. The *uvbyβ* measurements were also done with the 1 m telescope at the Mount Laguna Observatory to obtain the colours of this star. A study of the light curve together with radial velocity data allowed determination of a mass of 1.317 $M_{\odot}$ for the primary and 1.072 $M_{\odot}$ for the secondary. The absolute parameters led to the conclusion that the components are main-sequence stars of an age of about 2.5 billion years.

A combined spectroscopic and photometric study (though in one filter only) was published by Torres & Lacy (2009) and physical parameters of components were derived as 1.4 and 1.1 $M_{\odot}$ and 1.5 and 1.0 $R_{\odot}$ for the primary and secondary, respectively.

VZ Cep was found to be an X-ray source (Clausen et al. 2009) and was cross-identified with the ROSAT 215012.8+712639 object and also with the 2MASS J21501114+7126383 (Haakonsen & Rutledge 2009).

V881 Per

The variability of V881 Per (GSC 2846 0404) was discovered by the first Robotic Transient Search Experiment (Woźniak et al. 2004). Li & Hu (1998) investigated the system during the weak-lined T Tauri star candidates research and determined the spectral type of the system as K0IV, using the data obtained at the 2.16 m optical telescope at the Xing-Long station of the Beijing Astronomical Observatory. It was identified as a possible optical counterpart of 1RXS J025952.4+380149 X-ray source.

Otero, Wils & Dubovsky (2004), using the Northern Sky Variability Survey (NSVS), presented the system's light curve, defined it to be of EW/KW type and determined its period as 0.387 374 d.

Table 1. Linear elements used for phasing observations.

System	Reference epoch (HJD)	Period (d)
AP And	245 2500.2120	1.587 2911
VZ Cep	245 2500.9806	1.183 3637
V881 Per	245 2500.1272	0.387 3778

Table 2. Log of photometric observations.

System	Site	Comparison	Dates	No nights
AP And	Athens	TYC 3639-767-1	2011 Oct	7
VZ Cep	Athens	TYC 4470-1497-1	2011 Aug/Sep	6
V881 Per	Athens	TYC 2846-786-1	2011 Sep	7
V881 Per	Suhora	GSC 2846-786	2011 Oct/Dec	5

The light curve showed a strong O'Connell effect and an asymmetric secondary minimum. A new light curve was published by Norton et al. (2007) gathered by the Super Wide Angle Search for Planets (WASP) program. Its shape, however, was very different than that of Otero et al. (2004) with symmetric secondary minimum and much weaker O'Connell effect.

Based on the shape of V881 Per light curve, Hoffman, Harrison & McNamara (2009) suggested this system to be either a heavily spotted W UMa-type or a RS CVn-type system. The most recent study of this system was published by Nelson (2012), who determined its spectroscopic mass ratio ($q = 0.79$) and the physical parameters from the modelling of the *VRI* light curves. The model indicated the system's geometry to be detached and the asymmetry of the light curve to be caused by a spot (located on the secondary component).

2 PHOTOMETRIC OBSERVATIONS

New photometric observations were obtained at the University of Athens Observatory (AP And, VZ Cep and V881 Per) and Mt Suhora Observatory of the Pedagogical University (V881 Per). Complete, multicolour light curves for each system were obtained with the same CCD camera and filter set. Data for AP And and V881 Per were taken with a 40 cm Cassegrain telescope equipped with a ST-10XME CCD camera and a set of *BVRI* (Bessell) filters. All wide band data were taken in the fall of 2011. Observations of VZ Cep were carried out with a 25 cm Newtonian reflector telescope and a ST-8XMEI CCD and wide band *BVRI* filters. The light curve of AP And was completed within seven nights between October 2 and 20; VZ Cep, within six nights between August 30 and September 11, and V881 Per, in seven nights between September 13 and 30. The V881 Per binary was additionally observed at Mt Suhora using the 60 cm telescope with an Apogee Alta U47 CCD camera and a set of Strömgren *vby* filters. Details about the ephemeris used for phase calculations and log of photometric observations are given in Tables 1 and 2, respectively. For AP And we obtained 663, 675, 610 and 678 individual measurements in *B*, *V*, *R* and *I* filters, respectively. For VZ Cep, we obtained 454, 452, 447 and 461 points in *B*, *V*, *R* and *I* filters, respectively. V881 Per was observed in seven filters: 499 points were gathered in *B* filter, 503 in *V*, 481 in *R*, 488 in *I*, 553 in *v*, 601 in *b* and 607 in *y* filter.

3 SPECTROSCOPIC OBSERVATIONS

The spectroscopic observations were carried out at the Dominion Astrophysical Observatory (DAO), Canada using the Plaskett

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Table 3. Radial velocity measurements for AP And and VZ Cep.

HJD	Phase	Primary	Secondary
		AP And	
245 3994.9428	0.6843	114.4 ± 1.3	− 119.3 ± 1.1
245 4000.6869	0.3030	− 113.2 ± 1.0	114.2 ± 1.3
245 4364.8739	0.7423	126.5 ± 3.4	− 120.3 ± 2.6
245 4364.9196	0.7712	122.7 ± 3.4	− 123.7 ± 2.6
245 4364.9655	0.8000	116.7 ± 2.5	− 114.6 ± 1.7
245 4365.7851	0.3164	− 110.1 ± 1.7	114.5 ± 2.5
245 4365.8388	0.3502	− 99.2 ± 2.4	100.5 ± 2.3
245 4367.9029	0.6506	97.4 ± 2.4	− 107.5 ± 2.7
245 4369.6913	0.7773	121.6 ± 2.8	− 120.5 ± 1.7
245 5100.6517	0.2853	− 121.2 ± 3.5	116.8 ± 8.2
245 5106.9895	0.2781	− 126.9 ± 4.3	114.5 ± 4.4
245 5111.6495	0.2138	− 111.0 ± 2.2	104.1 ± 2.2
245 5111.7460	0.2747	− 122.0 ± 1.9	121.1 ± 2.7
		VZ Cep	
245 3633.7829	0.2730	− 120.1 ± 2.6	144.5 ± 1.7
245 3633.8177	0.3025	− 116.5 ± 2.8	137.3 ± 1.9
245 3633.8739	0.3499	− 95.9 ± 2.8	119.9 ± 2.5
245 3633.9236	0.3919	− 76.4 ± 2.5	94.1 ± 2.9
245 3633.9693	0.4305	− 52.9 ± 2.5	62.6 ± 3.5
245 3634.8100	0.1410	− 101.0 ± 2.7	107.0 ± 2.7
245 3634.8100	0.1410	− 101.9 ± 2.3	105.2 ± 1.6
245 3634.8585	0.1819	− 115.8 ± 2.5	126.3 ± 2.3
245 3634.9010	0.2179	− 123.7 ± 2.6	137.3 ± 1.7
245 3635.7579	0.9420	34.6 ± 3.0	− 70.7 ± 2.1
245 3636.7452	0.7762	101.8 ± 2.6	− 162.4 ± 3.9
245 3636.7911	0.8151	95.3 ± 2.8	− 148.6 ± 3.2
245 3636.8337	0.8511	84.3 ± 4.4	− 131.9 ± 4.9
245 3636.8784	0.8888	72.3 ± 3.5	− 110.7 ± 3.0
245 3637.7577	0.6318	83.0 ± 2.7	− 116.4 ± 3.3
245 3637.8002	0.6678	101.2 ± 2.7	− 132.7 ± 3.4
245 3637.8428	0.7038	109.4 ± 2.6	− 144.5 ± 4.4
245 3637.8853	0.7397	114.4 ± 2.5	− 153.6 ± 4.4
245 3638.9514	0.6406	85.5 ± 2.9	− 124.5 ± 3.4
245 3641.8510	0.0908	− 68.2 ± 2.4	76.5 ± 3.4

Table 4. Orbital parameters.

Parameter	AP And	VZ Cep	V881 Per
K_1 (km s^{-1})	123.2 ± 1.1	117.5 ± 1.2	142.5 ± 2.9
K_2 (km s^{-1})	122.1 ± 1.1	150.6 ± 1.2	173.7 ± 3.1
$V\gamma$ (km s^{-1})	− 0.9 ± 0.7	− 7.0 ± 0.7	− 4.0 ± 1.8
$a_1 \sin i$ (au)	0.0180 ± 0.0002	0.0128 ± 0.0001	0.0051 ± 0.0001
$a_2 \sin i$ (au)	0.0180 ± 0.0002	0.0163 ± 0.0001	0.0062 ± 0.0001
$m_1 \sin i$ ($M_\odot$)	1.209 ± 0.024	1.325 ± 0.025	0.697 ± 0.029
$m_2 \sin i$ ($M_\odot$)	1.219 ± 0.024	1.034 ± 0.021	0.572 ± 0.025
Mass ratio (q)	1.008 ± 0.013	0.780 ± 0.010	0.821 ± 0.022

1.82 m telescope equipped with a spectrograph at the Cassegrain focus and the SITe-2 CCD camera. The available combinations for grating and blaze angle resulted in a resolving power of $R \sim 10\,000$. The broadening functions method (Rucinski 2004) was used to obtain radial velocities for each target (Nelson, Terrell & Gross 2006; Nelson 2010). The obtained radial velocities were subsequently corrected for phase smearing using the method described by Nelson (2012). The radial velocities and their errors for two systems (AP And and VZ Cep) are listed in Table 3, while those for V881 Per have already been published by Nelson (2012). Finally, the orbital parameters were calculated and they are presented in Table 4. The values shown in this table were derived assuming circular orbits. Theoretical and observed radial velocity curves are displayed in Fig. 1.

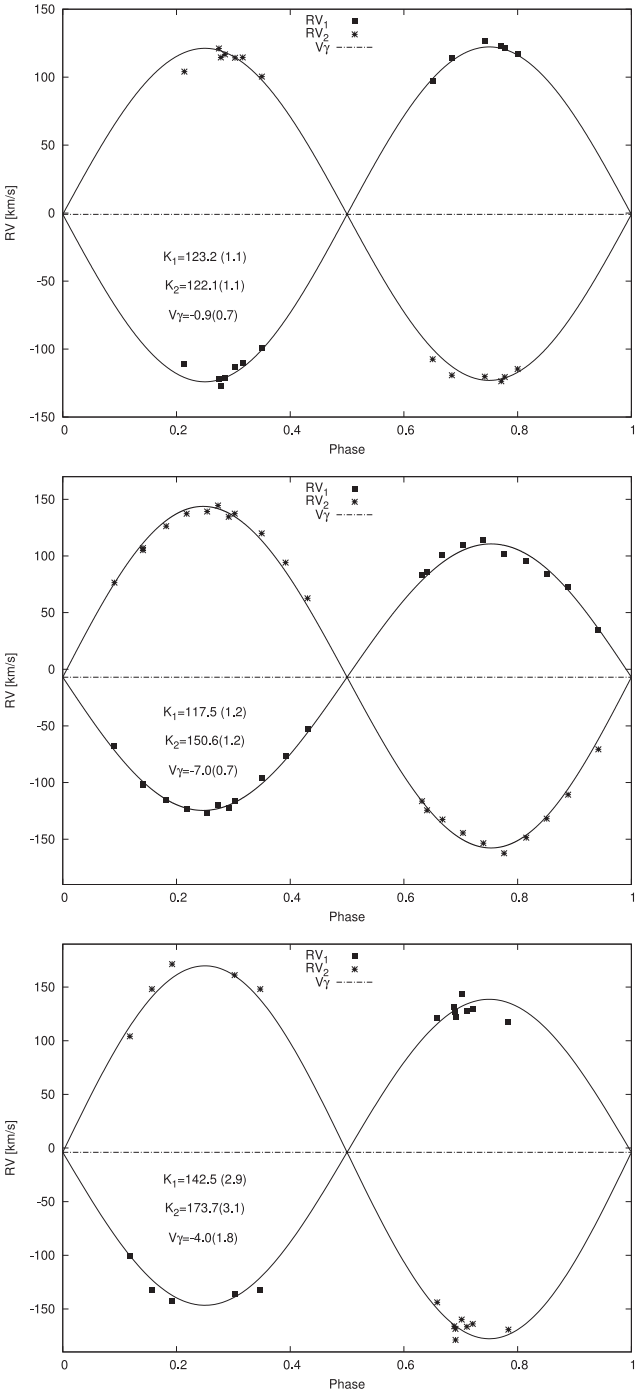


Figure 1. Radial velocity curves of AP And (top panel), VZ Cep (middle panel) and V881 Per (bottom panel). Squares and asterisks denote measured values, while the solid lines represent sinusoidal fits.

4 LIGHT-CURVE MODELLING

We performed the light-curve modelling using the Wilson–Devinney (w-d) code (Wilson & Devinney 1971; Wilson 1990). The code was modified by adding a Monte Carlo algorithm as a search procedure, while recently published limb-darkening

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coefficients were built into the code (Claret & Bloemen 2011). This code has been extensively used for derivation of physical parameters of few dozens of contact and close binaries. More detailed description can be found in the paper by Zola et al. (2010) and references therein. The mass ratio of the system was kept fixed according to the spectroscopic mass ratio obtained in this study. The temperature of the primary component was estimated using the spectral type – temperature calibration published by Harmanec (1988), according to the spectral classification from the literature. Since the Monte Carlo search procedure does not require any starting values for adjusted parameters (it searches for the best solution within a given range), we selected wide ranges to cover any probable values. The following parameters were adjusted during iterations: orbital inclination (i), temperature of the secondary component (T_2), potentials ($\Omega_{1,2}$), the luminosity of the primary (L_1) and spots, if a spot or spots were added into a model. Additionally, the phase shift parameter was adjusted.

The AP And and VZ Cep data have been phased using the ephemerides from Kreiner (2004) data base available online at the following address: http://www.as.up.krakow.pl/ephem/. The linear elements used for AP And were: $M_0 = 245\,2500.2120$ and $P = 1.587\,291\,09$ d, while these for VZ Cep: $M_0 = 245\,2500.9806$ and $P = 1.183\,3637$ d. For phasing the data of V881 Per, we recalculated the ephemeris of this system. To do this, we used all available minima times in the literature and those which were determined from our new observations. We also determined the primary minima times from best covered minima found in the public WASP archive (Butters et al. 2010). We found the V881 Per system period constant, and the corrected linear elements which were used for phasing this system data are

$$\text{Minimum (JDhel)} = 245\,2500.1272(2) + 0.387\,377\,85(4).$$

In order to speed up computations, mean points (130–180, depending on the filter) were calculated from all individual observations.

Computations for each system were performed simultaneously for all filters used in observations. The symmetric light curve of AP And did not require any spot assumptions into solution and a very good description of observations (see Fig. 2) was obtained.

The light curve of VZ Cep exhibits light level difference between two maxima. We tried a solution without a spot but the fit was

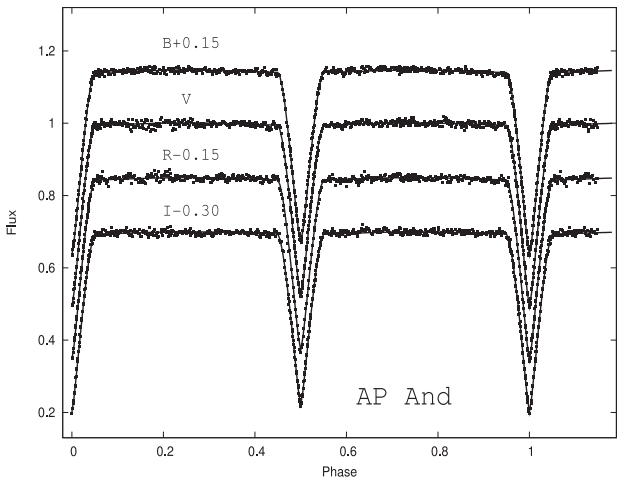


Figure 2. Comparison between theoretical and observed light curves of AP And (*BVRI* filters). Symbols represent individual observations, while theoretical light curves are shown as solid lines.

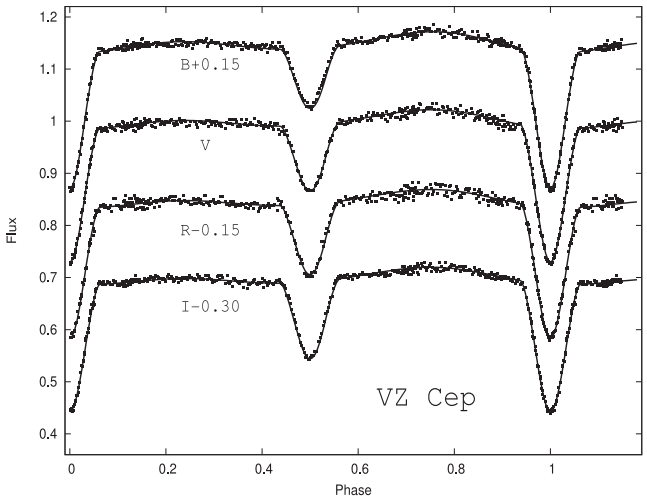


Figure 3. The same as for Fig. 2 but for VZ Cep.

poor. Therefore, following arguments of Torres & Lacy (2009) who considered the primary star to be too hot to have spots, a cool spot was placed on the surface of the secondary component and this improved the final fit shown in Fig. 3. Additionally, a model with two cool spots was also tried but the improvement of the fit over that derived within the one spot model was not significant.

The light curve of V881 Per was reported to vary significantly in shape. Our observations (see Fig. 4) do not show a light curve as distorted as that reported in NSVS, and in some way it is similar to that published by Nelson (2012). Nevertheless, the difference in maxima (the O'Connell effect) is noticeable and no suitable solution can be obtained if no spot is taken into account. Since the time-gap between the two new data sets is about two months, initially, we performed the light-curve modelling separately for each of them. For each data set, we made two trials, under the assumption of one and two cool spots placed on the surface of the primary (hotter) component. Both solutions resulted in acceptable fits, but the one with two spots turned to be somewhat better, as the number of free parameters is larger. Since the improvement in the fit was not large enough to justify an addition of four more free parameters, we decided to present the one-spot model as the final one. As the result, within the errors, we derived similar parameters for components as well as the orbital inclination and the spot location for both sets of observations.

The only parameter that differs in these solutions was the spot temperature: for the wide band data, we obtained the spot temperature factor of about 0.78, while for mid-band, Strömgren light curves taken two months later only yielded the value of 0.22. The final results derived from the light-curve modelling for all three systems are given in Table 5. For V881 Per, we present solutions for both sets of new data and that derived by Nelson (2012) for comparison. The views (perpendicular to the orbital plane) of the configurations of each system are shown in Fig. 5. The 3D models have been done using the BINARY MAKER version 3 software written by David H. Bradstreet and David P. Steelman (http://www.binarymaker.com).

5 DISCUSSION OF RESULTS AND CONCLUSIONS

As a result from our simultaneous analysis of spectroscopic and photometric data, we derived the physical parameters for the

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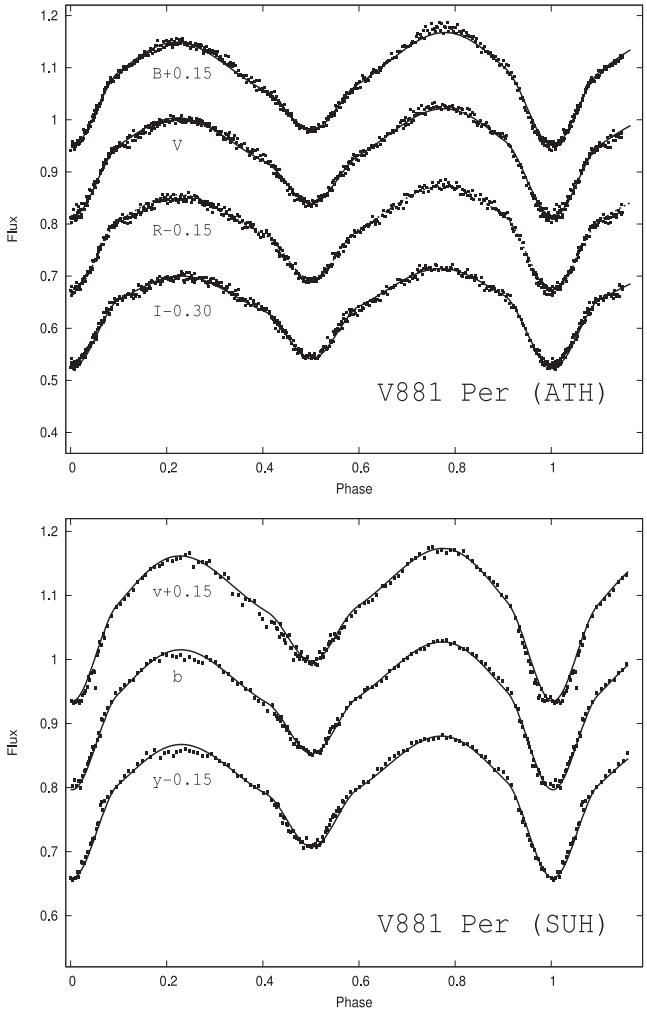


Figure 4. The same as for Fig. 2 but for V881 Per. The top panel shows light curves in *BVRI* filters, while those taken in Strömgren *vby* are displayed in the bottom one.

components of three systems, which are given in Table 6. The errors of parameters were estimated at the 90 per cent confidence level. Parameters listed for V881 Per are mean values for the two solutions presented in the previous section.

Out of the three systems considered, the light curve of AP And turned out to be the least complicated. The solution of the light curve required neither a third light nor any spots. The resulting theoretical light-curves fit observations in all filters very well (see Fig. 2). The orbit of this system is seen almost exactly edge on (derived inclination is 89°.5) and its configuration is detached. The components of AP And have almost equal masses with the primary star being hotter by just 60 K and slightly larger than the secondary.

The light curve of VZ Cep shows a pronounced O'Connell effect (Kallrath & Millone 1999). One cool spot is adequate to account for this asymmetry. The spot is located near the pole, at colongitude of 86° and radius of 46° and a temperature factor of about 0.71. Our spectroscopic solution agrees very well with that published by Torres & Lacy (2009). We obtained almost the same value for the semi-amplitude of the secondary but a smaller (by 1.4 km s^{-1}) value for that of the primary leading to a slightly smaller system mass ratio. The resulting physical parameters which are based on combined spectroscopic data and the new four colour light curve (these of Torres & Lacy 2009, utilized only a single colour light curve) are somewhat different. Comparing our absolute parameters with these published by Torres & Lacy (2009), we obtained about 2–3 per cent smaller values for masses of components, mainly a result of about 1°.5 higher system inclination resulting from our solution. We derived about 6 per cent larger radius of the primary star while that of the secondary is almost 10 per cent smaller. Torres & Lacy (2009) made a thorough discussion of the evolutionary status of VZ Cep and by comparing their results with theoretical models found the secondary star to be too cool. Our results indicate even larger difference between the temperatures of components (1070 K versus 950 K derived by Torres & Lacy 2009) even more challenging for the theories of stellar evolution. The presence of the spot indicates some magnetic activity, likely the source of X-ray radiation observed from this system (Clausen et al. 2009).

V881 Per is the most interesting system analysed in this paper. The available references indicate huge variability of the system's light curve. The WASP light curve published by Norton et al. (2007) is almost symmetrical with barely noticeable difference of the maxima. On the other hand, the NSVS project light curve (Otero et al. 2004) is very distorted with the well-visible O'Connell effect reaching almost 0.1 mag (the second maximum is lower in brightness). Our new data show also a difference in maxima brightness but only of about 0.025 mag, and contrary to the NSVS light curve, the level of the first maximum is lower than the second one. We consider it worth checking if all available light curves can be reproduced with the same model differing only in spot(s) parameters. Except for the new data we recently gathered, we analysed also the NSVS and WASP light curves. The WASP public archive data for V881 Per confirmed its high variability, and it turned out impossible to do light-curve modelling of the whole set. Therefore, we divided the data into three subsets in the following ranges (in JD): 245 3204.68–245 3258.64 (R1), 245 3994.55–245 4020.73 (R2), 245 4021.76–245 4111.38 (R3) and 245 4348.66–245 4458.57 (R4). For these chosen ranges, visual inspection of the light-curve shape indicated roughly the same shape, with some scatter, however. The NSVS data were obtained over the period of JD245 1370.87–JD245 1630.64, while the Athens Observatory data were collected between JD245 5818.39 and JD245 5835.62 and the Mt Suhora Observatory data were taken from JD245 5839.34 to JD245 5916.48. The data were phased with the ephemeris listed in Section 4 and the light curve modelling was performed for data in each of the three ranges. In these computations only phase shift, luminosity of the primary component and the spot parameters, except the spot temperature factor, were adjusted. Due to the data being taken in one filter, it would not be possible to get reliable value for the spot temperature, and we fixed this parameter at 0.8 (ratio of the spot temperature to the surrounding stellar surface). Other parameters were kept fixed at the mean values resulting from the Athens and Suhora data computations: $i = 66°.2$, $T_1 = 5200$ K, $T_2 = 4350$ K, $\Omega_1 = 3.603$, $\Omega_2 = 4.124$ and $q = 0.821$. It turned out that for all of data sets, we were able to obtain reasonable fits (see Figs 6–10). For all data sets, except for WASP R1, the models with cool spot(s) described observed data well. However, for light curve in the R1 region we failed to obtain a good fit – the depth of one or both minima were too shallow and the fit was very poor. As it did not help to allow the spot parameter to be adjusted, we had to increase the range of the spot's temperature factor, to allow also spots hotter than the surrounding surface. Only then our solution resulted in a good fit (see Fig. 7); this involved one cool and one hotspot. The derived spot(s) parameters are listed in Table 7.

Nelson (2012) presented a model of V881 Per which included a cool spot placed on the equator of the secondary component.

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Table 5. Results derived from the light-curve modelling.

Parameter	AP And	VZ Cep	V881 Per (ATH)	V881 Per (SUH)	V881 Per (Nelson 2012)
Phase shift	0.0001 ± 0.0001	−0.0014 ± 0.0002	0.0016 ± 0.0003	0.0028 ± 0.0004	0.0063 ± 0.0005
i [deg]	89.5 ± 0.1	81.4 ± 0.4	65.9 ± 0.3	66.5 ± 0.3	61.96 ± 0.23
T_1[K]	* 6340	* 6700	* 5200	* 5200	* 5150
T_2[K]	6280 ± 10	5630 ± 30	4330 ± 25	4370 ± 21	4576 ± 65
Ω_1	7.340 ± 0.040	4.725 ± 0.029	3.599 ± 0.006	3.608 ± 0.009	3.675 ± 0.017
Ω_2	7.621 ± 0.044	6.420 ± 0.137	4.081 ± 0.043	4.167 ± 0.044	3.412 ± 0.019
$q_{\rm spec}(m_2/m_1)$	* 1.009	* 0.781	* 0.821	* 0.821	* 0.7928
$L_1(B)$	6.620 ± 0.065	11.174 ± 0.078	10.887 ± 0.125	$L_1(v)$ 10.705 ± 0.090	
$L_1(V)$	6.632 ± 0.066	11.000 ± 0.082	10.754 ± 0.123	$L_1(b)$ 10.689 ± 0.090	$l_1(V)$ 0.682 ± 0.003
$L_1(R)$	6.606 ± 0.068	10.816 ± 0.086	10.583 ± 0.120	$L_1(y)$ 10.625 ± 0.091	$l_1(R)$ 0.651 ± 0.003
$L_1(I)$	6.582 ± 0.070	10.624 ± 0.093	10.141 ± 0.116		$l_1(I)$ 0.630 ± 0.003
$L_2(B)$	** 5.864	** 1.583	** 1.835	$L_2(v)$ ** 1.835	
$L_2(V)$	** 5.905	** 1.775	** 2.068	$L_2(b)$ ** 2.068	$l_2(V)$ ** 0.318
$L_2(R)$	** 5.918	** 1.921	** 2.279	$L_2(y)$ ** 2.279	$l_2(R)$ ** 0.349
$L_2(I)$	** 5.949	** 2.130	** 2.637		$l_2(I)$ ** 0.370
			Spot parameters		
Colatitude [deg]		155.0 ± 13.3	169.4 ± 0.7	170.5 ± 0.7	* 90.0
Longitude [deg]		86.1 ± 3.2	196.2 ± 0.9	196.7 ± 1.3	294 ± 5
Radius [deg]		46.4 ± 6.9	68.8 ± 0.7	58.6 ± 0.8	33.5 ± 0.5
Temp. factor		0.71 ± 0.14	0.78 ± 0.02	0.22 ± 0.12	0.8985 ± 0.0077
$r_1^{\rm side}$	0.1583 ± 0.0010	0.2558 ± 0.0022	0.3685 ± 0.0001	0.3684 ± 0.0013	0.3353 ± 0.0054
$r_2^{\rm side}$	0.1594 ± 0.0078	0.1473 ± 0.0037	0.2834 ± 0.0043	0.2694 ± 0.0039	0.3517 ± 0.0008

∗ – assumed, ∗∗ – computed

L_1, L_2: w-d program input values – the subscripts 1 and 2 refer to the star being eclipsed at primary and secondary minimum, respectively. Spot parameters refer to the larger and more massive component.

The resulting parameters derived by Nelson (2012) for V881 Per are given in the last column for comparison. Note that the spot was assumed to be on the secondary component.

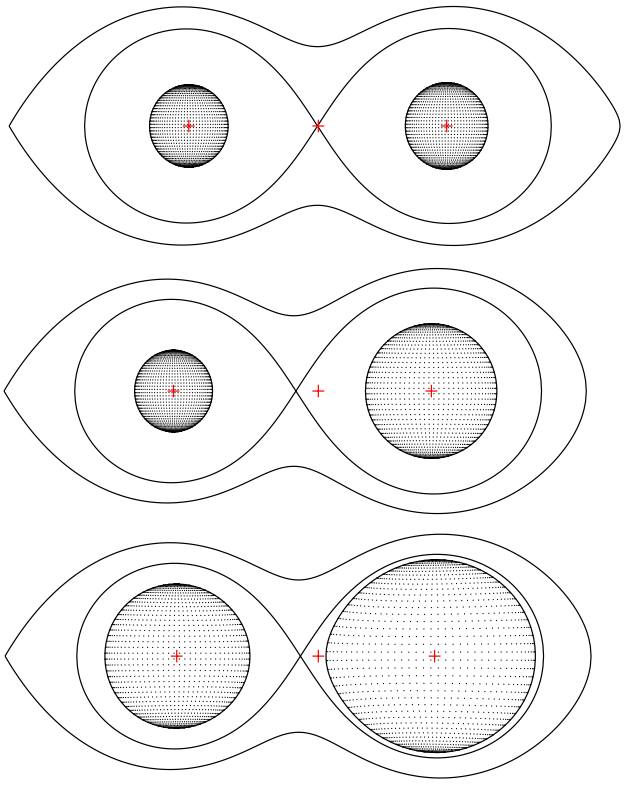


Figure 5. View of the models of AP And (upper panel), VZ Cep (middle panel) and V881 Per (bottom panel). The Roche and outer critical lobes as well as barycentres (crosses) are also shown.

Our computations had no such restriction – the entire surface of the primary star was searched for a spot location that would give the best fit to the observed light curves. For our new light curves, both ATH and SUH, the preferred spot location was near the pole. We also checked how good a solution would be when a spot was forced to be on the equator. For all light curves except of NSVS, for which fits are comparable, the description of observed light curves was significantly better with spots at the polar region of the primary. The main differences between Nelson's and our solutions are in system inclination and potential of the secondary. The inclination resulting from our solution is about 4° higher. The system configuration derived by Nelson (2012) was detached but very close to semidetached with the secondary filling in (within the error) its Roche lobe and both components having similar radii. We derived a detached configuration and the secondary component size smaller than that of the primary. We fixed the potential of the secondary star at its Roche value and repeated computations in order to check if our search procedure did not miss that solution. We did this for both ATH and SUH data but it turned out that a better fit to the new observations (smaller reduced χ^2) was that for the detached configuration found with extensive Monte Carlo search when also potential of the secondary was treated as a free parameter and this solution is presented as the final one.

Reliability of solutions derived for the systems analysed depends on which model has been applied to each binary. In the case of AP And, whose light curve shows no trace of asymmetries and a non-spotted model fits it very well, the system parameters were obtained with the least uncertainty. Introducing a spot always deteriorates the possibility of convergence at a unique solution. Using a global search method (e.g. Monte Carlo or genetic algorithms) assures that

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Table 6. Absolute parameters of the studied systems (in solar units).

System	A	$\mathcal{M}_1$	$\mathcal{M}_2$	R_1	R_2	$\mathcal{L}_1$	$\mathcal{L}_2$
AP And	7.698 ± 0.069	1.211 ± 0.024	1.222 ± 0.024	1.218 ± 0.013	1.226 ± 0.061	2.117 ± 0.141	2.067 ± 0.206
VZ Cep	6.343 ± 0.051	1.376 ± 0.027	1.073 ± 0.023	1.622 ± 0.019	0.934 ± 0.025	4.683 ± 0.301	0.774 ± 0.044
V881 Per	2.647 ± 0.055	0.912 ± 0.039	0.748 ± 0.035	0.975 ± 0.020	0.708 ± 0.018	0.614 ± 0.054	0.363 ± 0.020

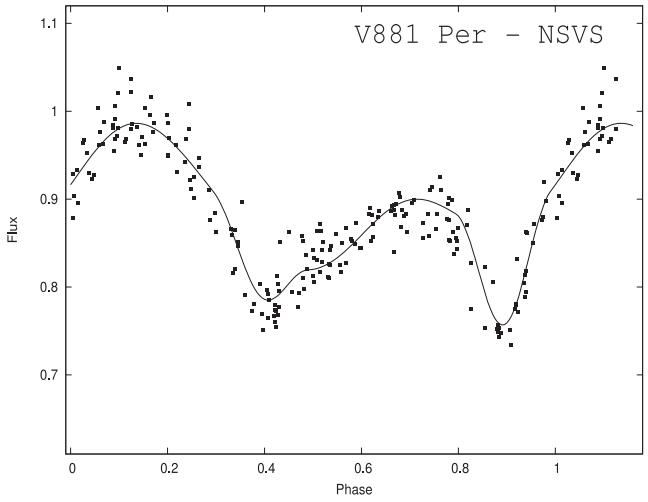


Figure 6. The light curve of V881 Per taken within the NSVS program. The line represents the best fit with spot parameters and luminosities being adjusted.

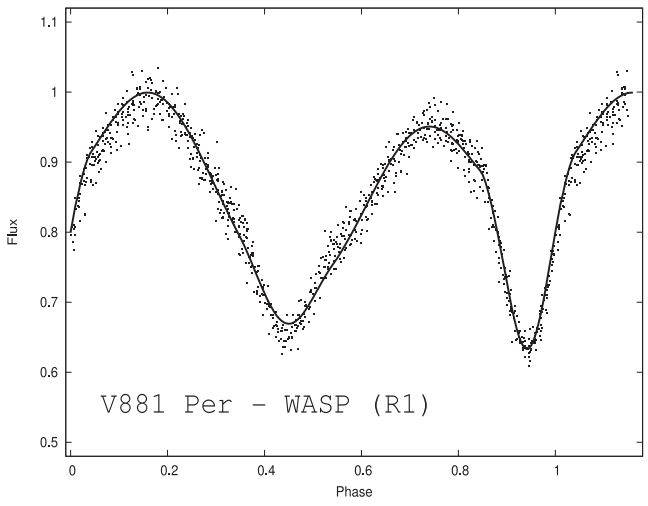


Figure 7. The same as in Fig. 6 but for WASP R1 data.

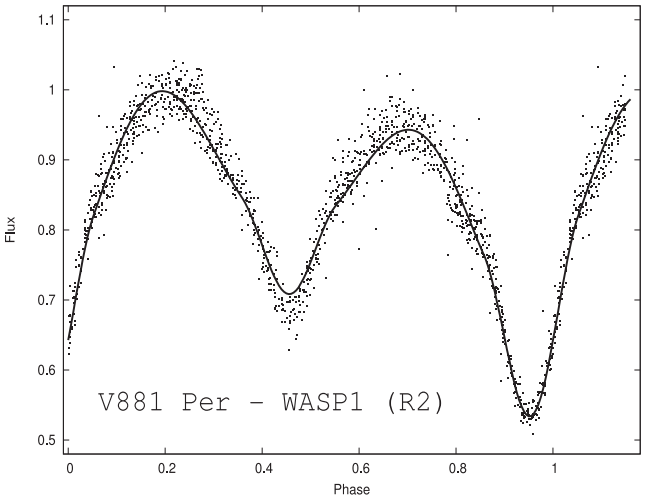


Figure 8. The same as in Fig. 6 but for WASP R2 data.

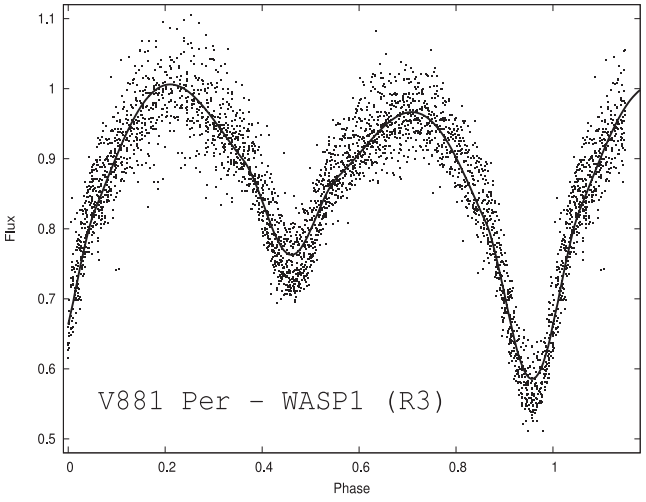


Figure 9. The same as in Fig. 6 but for WASP R3 data.

a solution found for given data is the one which fits them the best. However, if a spot is present on a component of a binary system, even using such methods, cannot provide solutions equally reliable as in the case of unspotted stars. This is due to strong correlations among parameters describing a spot, especially these for the spot latitude, its radius and the temperature. Following the suggestion of a referee, we made fits to light curves separately in each filter. The resulting spot parameters derived in each filter for both VZ Cep and V881 Per are presented in Table 8.

The values for the spot longitude, the parameter which can be derived most reliably, span over 22° for VZ Cep. Other three spot parameters are highly correlated (e.g. very similar fits can be obtained for a smaller but cooler spot or a larger one but with a higher temperature). Still, the individual filter solutions are within 22° range for the spot colatitude and 13° for its radius. Since the fits were done in single filters, one cannot expect that a reliable spot temperature could be derived. The solutions for V881 Per seems to be better constrained, especially these for the *BVRI* data. The ranges in which the solutions converged are smaller, about 17° for the spot longitude, but if the result for the v filter (having the lowest S/N ratio) is not considered, the values for this parameter scatter over the 7° range. Similarly, the values for the spot colatitude and its radius were derived within a range of few degrees.

Finally, this exercise produced information how these different models that include a spot influence the resulting system parameters. In the case of VZ Cep, we obtained inclination in the 80.°5–81.°6 range, temperature of the secondary was derived between 5530 and 5670 K, potential of the primary between 4.731 and 4.815, while

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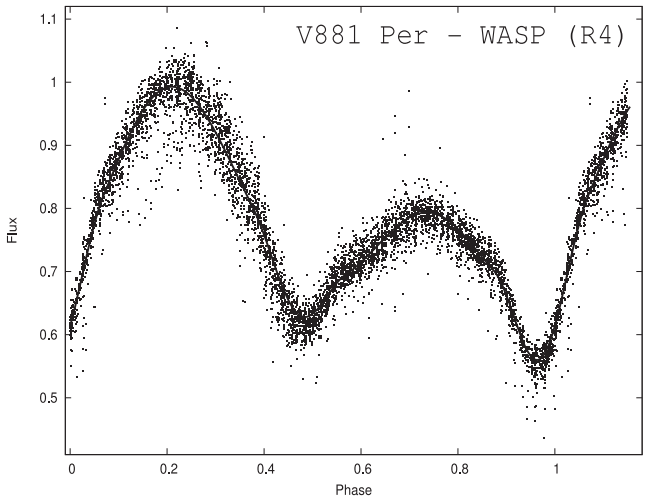


Figure 10. The same as in Fig. 6 but for WASP R4 data.

Table 7. V881 Per spot(s) parameters in different seasons.

Observations	Colatitude (deg)	Longitude (deg)	Size (deg)	Temperature factor
NSVS	160	119	69	0.80
WASP R1	178	313	74	1.38
	150	173	44	0.22
WASP R2	116	183	52	0.80
	22	11	67	0.80
WASP R3	139	175	63	0.80
	16	0	75	0.80
WASP R4	14	49	76	0.80
	122	176	47	0.80
ATH	169	196	69	0.78

Table 8. Resulting spot parameters derived for each filter separately.

Filter	Colatitude (deg)	Longitude (deg)	Size (deg)	Temperature factor
		VZ Cep		
B	144.8	88.4	38.5	0.25
V	162.6	94.6	51.3	0.24
R	166.7	77.9	50.7	0.49
I	159.3	87.0	44.7	0.38
		V881 Per		
B	167.3	199.1	63.7	0.17
V	167.4	199.2	63.9	0.63
R	169.1	198.9	62.5	0.22
I	169.2	193.3	59.7	0.16
v	161.8	187.2	44.8	0.43
b	167.9	201.1	55.4	0.13
y	167.8	204.1	58.3	0.29

that for the secondary between 6.111 and 6.711. The results for V881 Per are inclination between 64.°5 and 65.°9, temperature of the secondary in the range (4350–4450 K), potential of the primary between 3.574 and 3.659 and that for the secondary between 3.872 and 4.126.

The evolutionary status of stars can be inferred from the mass–radius (M–R) and mass–luminosity (M–L) diagrams by comparing

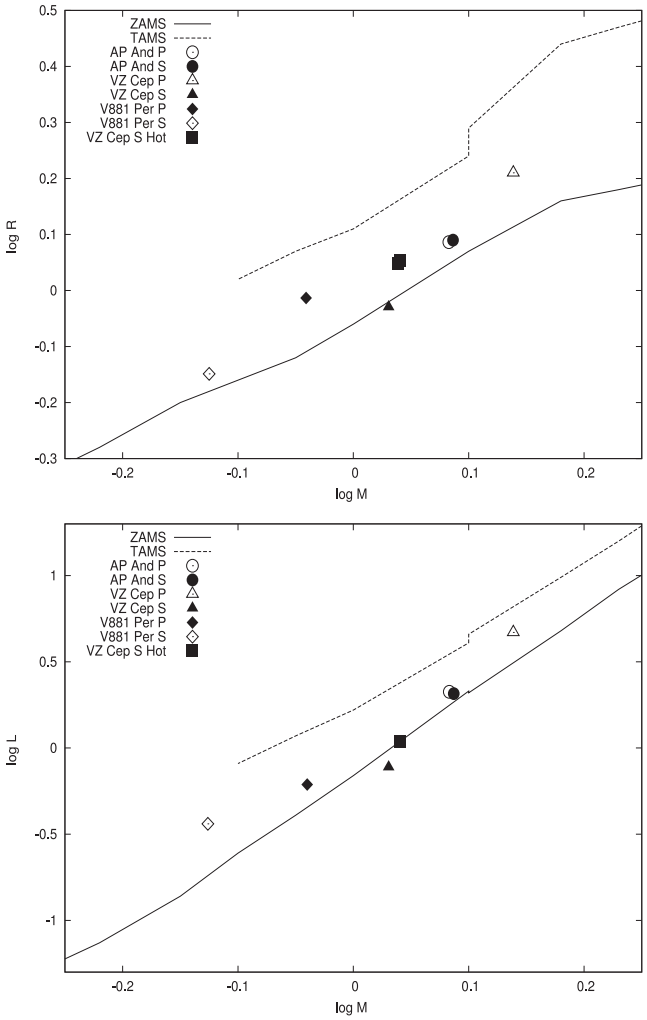


Figure 11. Mass–radius (top) and mass–luminosity (bottom) diagrams. Lines denote theoretical ZAMS and TAMS computed for the solar metallicity while symbols represent parameters of components (P – primary, S – secondary) of the three systems analysed in this work.

physical parameters with theoretical ones. We plotted the derived absolute parameters in Fig. 11 along with theoretical ones corresponding to zero-age main sequence (ZAMS) and terminal-age main sequence (TAMS) computed for the solar metalicity ($z = 0.02$) using the Geneva models (Schaller et al. 1992; Charbonnel et al. 1998). As it can be seen, the components of all three systems, with the exception of the secondary star in VZ Cep, are well inside the main-sequence band. The stars in AP And are unevolved and very similar concerning their mass and temperature with no evidence of mass transfer in the past. On the other hand, more massive components of VZ Cep and V881 Per are more evolved than the respective secondaries. However, these primaries are currently distorted (shown on the right in Fig. 5), and very probably in the future they will fill in their Roche lobes first and start to transfer mass to their companions.

The secondary star in V881 Per seems to be somewhat undersized (see the top panel of Fig. 11) for its mass. This underprediction of size of low-mass components of binaries by models, with this discrepancy being more and more significant for very low mass stars (reaching about 30 per cent for 0.2–0.4 $M_{\odot}$), was noticed a long time ago (Hoxie 1973; López-Morales & Shaw 2007). Further, the

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observed temperatures are lower than models predictions (Baraffe et al. 1998) and, therefore, luminosities of these low-mass stars seem not to deviate much from values computed from the standard models. A growing number of systems with low-mass components and with determined fundamental parameters, indicated that there might be two populations of low-mass stars: first, whose parameters agree well with models that do not account for presence of magnetic fields and second, the population of magnetic stars showing the above-mentioned discrepancy in their size and temperature. The hypothesis that magnetic fields can inflate the radii of stars with masses lower than $0.8\,M_{\odot}$ has been investigated by Feiden & Chaboyer (2013a,b). They found out that such a mechanism could work in stars with radiative cores and convective envelopes, though requires very strong stellar surface magnetic field, but not in fully convective stars.

VZ Cep deserves a special attention as determined parameters of the secondary place it below the ZAMS line in the M–L diagram and exactly on ZAMS in the M–R one (see Fig. 11). Masses of both components are above 1 solar mass and the secondary one is underluminous compared to the standard models. Concerning its lower luminosity, this is mostly the result of too low a temperature of the secondary star (noticed earlier by Torres & Lacy 2009). The single filter fits indicated higher scatter of the secondary star potential in the derived individual filters solutions. As the final step, we checked how many different values of parameters could be obtained by assuming not only the existence of a cool, but also a hotspot placed on either the secondary or the primary component. These computations were performed simultaneously in all four filters. It turned out, that the resulting radii of the secondary within the hotspot models (at either component) are significantly larger than these for a cool spot assumption. They are shown in the M–R and M–L diagrams (see Fig. 11) as squares. Within these solutions, the mass of the secondary is larger by about 3 per cent, and its luminosity is also larger, placing it exactly at the ZAMS stage. The largest increase was in the radius of the secondary component which is larger by about 20 per cent, with the new position in the M–R diagram to be between the ZAMS and TAMS lines.

We conclude that if there is magnetic activity in a system, this can complicate very much the solution of its light curves, even if the spectroscopically determined mass ratio is available. Furthermore, the derived absolute parameters of components can be biased by a systematic error and, therefore, they need to be reviewed with help of high-resolution spectra.

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